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IMPACT OF GMS-5 AND GOES-9 SATELLITE-DERIVED WINDS ON THE PREDICTION OF A NORPEX EXTRATROPICAL CYCLONE

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1 INTRODUCTION

In 1998, a major field campaign called NORPEX (NORth Pacific Experiment, 14 January - 27 February 1998) was conducted to study fierce winter storms that move eastward across the Pacific Ocean and pound the western United States. The NORPEX experiment collected several types of observations, such as GPS (Global Positioning System) dropsondes and GMS-5 and GOES-9 satellite wind data over the entire North Pacific. The geostationary satellite-derived wind data from multispectral imagery were available every 6 h for GMS-5 and every 3 h for GOES-9 over the North Pacific. These data were provided by the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) in conjunction with NOAA/NESDIS (Velden et al., 1997). Nowdays, the satellite derived winds are comprehensive regular source of atmospheric observations especially over oceanic regions.

The NORPEX cyclone to be studied initiated near the east coast of Asia on 12 UTC 19 February 1998 (around $126^oE, 32^oN$). In 3 days, the cyclone central pressure decreased from 1007 hPa to 945 hPa and obtained its maximum strength at 12 UTC 22 February 1998 over the middle of the North Pacific (around $173^oE, 50^oN$, in Fig. 1). The intensity remained for the following 12 hours. Afterwards, the cyclone began its period of decay. The potential vorticity (PV) anomaly above the cyclone shows a typical LC2 (Life Cycle 2) pattern of cyclogenesis.

The objective of this paper is to carry out a set of 4D-Var assimilation and adjoint sensitivity experiments to access the impact of the GMS-5 and GOES-9 satellite wind data upon the mid-Pacific oceanic cyclone development.

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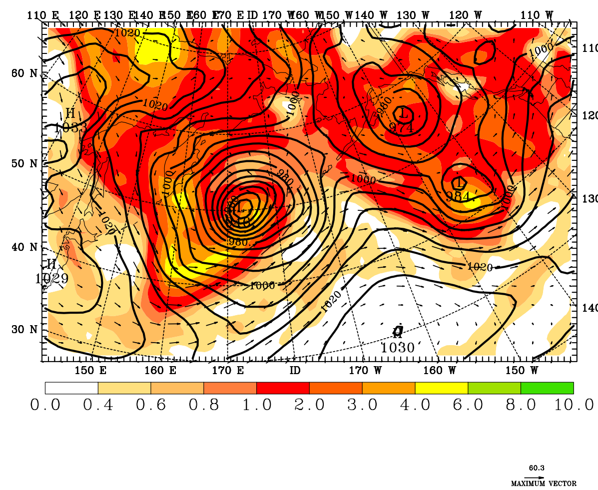

Figure 1: Analysis of sea-level pressure (thick line, interval 5 hPa), potential vorticity (shading with scale) and wind vectors at 300K θ layer at 12 UTC 22 February 1998.

2 4D-VAR EXPERIMENTS

2.1 Experimental design

MM5 4D-Var system (Zou et al. 1997; 1998) is used to carry out the experiments. The model domain (Domain A) covers the North Pacific basin (Fig. 2). The model grid-spacing for Domain A is 90 km, with 109X190X23 grid points. The 23-layer half σ levels are 0.010, 0.035, 0.065, 0.095, 0.125, 0.155, 0.190, 0.230, 0.275, 0.325, 0.380, 0.440, 0.505, 0.575, 0.645, 0.715, 0.785, 0.855, 0.910, 0.945, 0.970, 0.985, and 0.995. Starting from 12 UTC 19 February 1998, a 6-h assimilation window is used for the MM5 4D-Var system to incorporate the GMS-5 and GOES-9 satellite wind data. In this 6-h window, GMS-5 winds are available at 12 UTC and 18 UTC 19 February 1998, and GOES-9 satellite wind data are available at 12 UTC, 1500 UTC, and 18 UTC 19 February 1998. Two 4D-Var experiments are designed. One assimilates only the GMS-5 wind data, while another assimilates both the GMS-5 and GOES-9 satellite wind data. Twenty iterations are carried out. The minimization algorithm is the limited-memory quasi-Newton method (LBFGS) developed by Liu and Nocedal (1989).

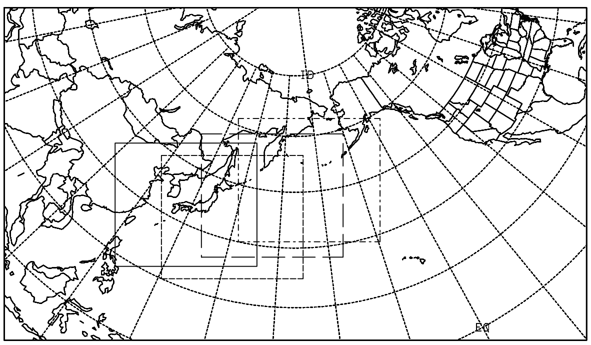

Figure 2: Model domains configuration for the experiments. Domain A is fixed with 109X190X23 dimension, Domain B is moved along the cyclone at 30h, 48h, and 60h, with dimension 121X139X23.

In order to examine the impact of the satellite-derived wind data on the cyclone forecast in the nested model configuration, some forecasts are carried out by nesting a 30-km resolution domain (Domain B) into Domain A (Fig. 2). The nested domain (Domain B) has grid points of 121X139X23. Domain B is moved at 36h, 48h, and 60h, following the cyclone movement.

Major physics options in the experiments are: Kuo (1974) cumulus parameterization for Domain A, Betts-Miller cumulus parameterization (Betts and Miller 1986) for Domain B; Blackadar (1979) high resolution models of the planetary boundary (Zhang and Anthes 1982) for both domains; large-scale precipitation parameterization scheme for Domain A while Dudhia's simple explicit moisture scheme for domain B; a simple radiation parameterization scheme for both Domain A and B. The choice of different schemes for Domain A or B is made based on our previous experience.

We summarized all the experiments conducted in this study as follows. CL1912 is a 90-km resolution, single domain control run starting at 12 UTC 19 February 1998. CH1912 is a nested-domain control run. GMSL, BOTHL, GMSH, and BOTHH are four 4D-Var experiments incorporating the satellite wind data. GMSL assimilates only GMS-5 winds. BOTHL assimilates both GMS-5 and GOES-9 winds. The forecasts of GMSL and BOTHL are both carried out in the 90-km single-domain. GMSH assimilates only GMS-5 winds, and BOTHH assimilates both GMS-5 and GOES-9 winds. However, the forecasts of GMSH and BOTHH are conducted with the nested-domains (90 and 30 km).

2.2 GMS-5 and GOES-9 winds

The satellite wind data are derived through application of automated tracking algorithms to water vapor (WV), visible (VIS), and infrared (IR) imagery from GMS-5 and GOES-9, as described in Velden et al. (1997), Nieman et al. (1997), and Velden et al. (1998). At 12 UTC 19 February 1998, The satellite wind data are distributed over the entire troposphere, but are largely concentrated in the upper troposphere, at or above 400 hPa (Fig. 3). Typically, about 70% of the multispectral winds are observed above 400 hPa, about 15% at 400 hPa, and about 15% below 400 hPa (Goerss et al. 1998). In the case we are studying (in Fig. 3), the maximum number of the wind targets are around 350-400 hPa for GMS-5 and 300-400 hPa for GOES-9.

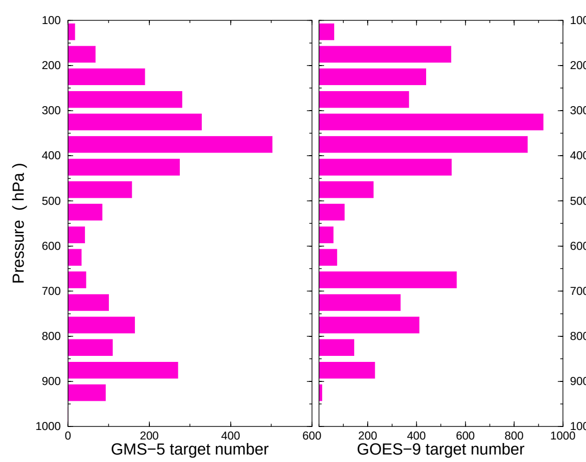

Figure 3: Statistics of target numbers for GMS-5 (left panel) and GOES-9 (right panel) satellite wind data at 12 UTC 19 February 1998.

The 4D-Var experiments includes GMS-5 winds at every 6 h and GOES-9 at every 3 h. It is anticipated that assimilation of the satellite wind data will add useful observational information to the initial conditions. Through model integration, the information could propagate to other levels upward and downward.

2.3 Impact of the satellite-derived winds on the storm forecast

Table 1 gives the position (intensity) errors of all experiments compared with NCEP analysis at 24-h interval. The forecasts of the cyclone position in GMSL and BOTHL are improved in 48 h and 72 h. For the one-day and two-day cyclone intensity forecasts, both GMSL and BOTHL yield an additional 1-3 hPa decrease of the cyclone central SLP compared with the control run CL1912. Such a decrease is, however, not seen in the last 24-h forecast. Generally speaking, the two 4D-Var experiments GMSL and BOTHL predicted the storm central pressure with similar intensity and trend as well. They also predicted a similar position. This indicates that the GOES-9 satellite-derived wind data downstream of the cyclone have marginal influence on the track and intensity of the upstream cyclone.

Table 1: Position (intensity) errors of the predicted cyclone compared with NCEP analysis

EXP	24 h	48 h	72 h
CL1912	254.56 km (5.7 hPa)	636.40 km (17.5 hPa)	702.92km (34.0 hPa)
CH1912	90.00 km (1.1 hPa)	201.25 km (2.00 hPa)	636.40 km (6.1 hPa)
GMSL	254.56 km (4.6 hPa)	576.28 km (14.8 hPa)	636.40 km (34.6 hPa)
BOTHL	254.56 km (4.6 hPa)	576.28 km (14.4 hPa)	636.40 km (35.3 hPa)
GMSH	180.00 km (0.5 hPa)	201.25 km (1.3 hPa)	458.91 km (3.7 hPa)
BOTHH	90.00 km (0.3 hPa)	201.25 km (0.9 hPa)	458.91 km (1.1 hPa)

The two experiments GMSH and BOTHH are equivalent to GMSL and BOTHL, respectively, except that a high-resolution (30 km) small domain is nested into the big domain and moves along the track of the cyclone. The nested domain experiments further improved the prediction of the cyclone, both in the intensity and position (Table

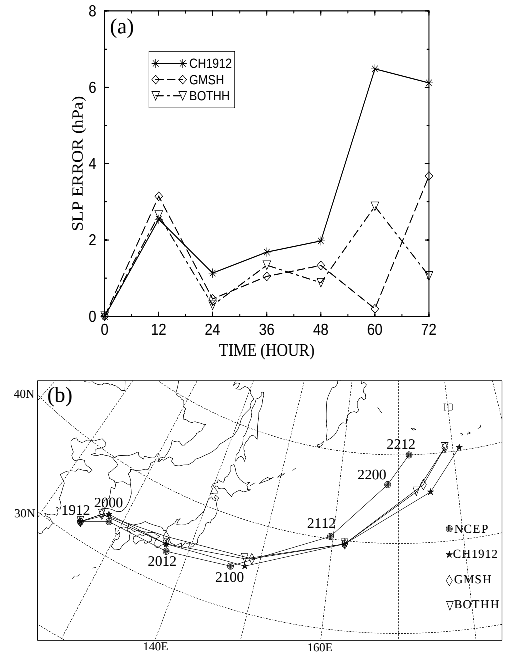

Figure 4: Nested-domain forecasts of (a) Sea-level pressure error compared with MM5 analysis and (b) cyclone track for GMSH (diamond), BOTHH (down triangle) and their control run CH1912 (star). The cyclone track from analysis is solid line with black dot at 12-h interval

1). Although data assimilation is carried out in the outmost single domain, the improvement of the cyclone in the nested-domain forecasts is more evident than that in the single-domain forecasts. Satellite data assimilation, and improved model resolution and physics together (GMSH and BOTHH), produced a good cyclone evolution. This indicates that one can benefit from using a simpler model with only one domain for the assimilation to reduce the computation expense and a nested domain model with more sophisticated model physics and higher model resolution for the forecast.

The simulated intensity error and track of the cyclone for CH1912, GMSH and BOTHH are plotted in Fig. 4. First of all, the nested control run CH1912 predicted the cyclone much stronger than the non-nested control run CL1912 (952 hPa vs. 979 hPa in 72-h forecast). The addition of satellite data further improved the cyclone intensity forecast in the nested experiments (GMSH and BOTHH). The predicted central SLP of the cyclone at 12 UTC 22 February 1998 (72-h forecast) is 941 hPa for

GMSH and 946 hPa for BOTHH, very close to the MM5 analyzed intensity (945 hPa). In addition, the cyclone track is also improved in the nested-domain experiments. Again, the cyclone tracks in GMSH and BOTHH are very similar, showing the GOES-9 satellite wind east of the international date line has little impact on the upstream cyclone track forecast. Both GMSH and BOTHH reduced the cyclone track from the nested-domain control experiment CH1912 (see Fig. 4 and Table 1).

3 ADJOINT SENSITIVITY ANALYSIS

The adjoint technique is a computationally efficient method to determine the sensitivity of the forecast with respect to model initial conditions. In sensitivity analysis, the model output of interest is usually referred to as the system's $response$, instead of being called a cost function as in data assimilation. We consider a functional response $R(\mathbf{x})$ of the form $R(\mathbf{x}) = -\sum_{i,j} p_s(i,j;t_R)$, where p_s represents the SLP at the time t_R (=12 UTC 22 February 1998), $\sum_{i,j}$ includes all model grid points in a 6×6 grid box centered at the surface low at 12 UTC 22 February 1998, and $\mathbf{x}$ is the model initial conditions at 12 UTC 19 February 1998 for the 72-h sensitivity studies.

The adjoint sensitivities are examined for the initial conditions (12 UTC February 1998), as determined by a backward integration of the adjoint model over 72 h. It is indicated that the sensitivity to both temperature and winds is largest over the East Asia coast and northwest Pacific region in the lower troposphere (Fig. 5). The vertical cross-sections also indicate that the sensitivities tilt westward with height (Fig. 5). The largest sensitivity to temperature ($\frac{\partial R}{\partial T}$) is around 800 hPa, while that to zonal wind ($\frac{\partial R}{\partial u}$) is found around 900 hPa. Closer to the surface, however, the sensitivity is damped by boundary-layer processes. Damping of near-surface perturbation growth is consistent with other adjoint sensitivity studies (Langland et al. 1995).

The sensitivity analysis shows that the cyclone intensity is more sensitive to zonal winds at lower levels than at higher levels. Due to the fact much less satellite wind data were available at lower levels (Fig. 3), the assimilation experiments carried out in this paper did not produce much further deepening of the cyclone at the 90-km resolution as was originally expected. More data from the lower troposphere are expected to produce a more significant impact on the forecast of the cyclone.

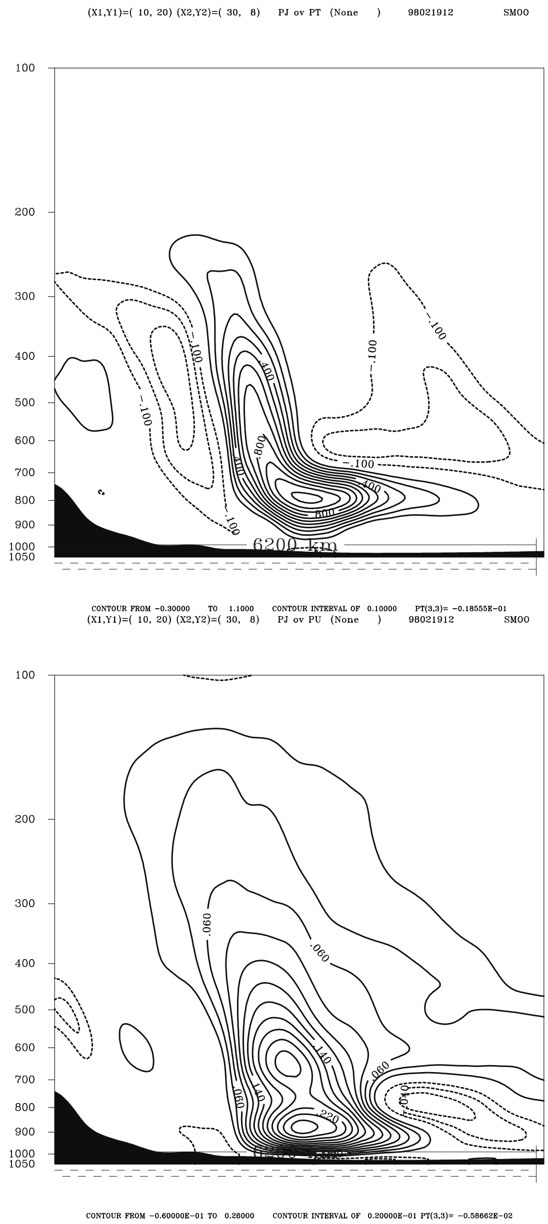

Figure 5: Cross-sections of the adjoint sensitivity to initial temperature (0.1 $hPa\ K^{-1}$, upper panel), and initial zonal wind (0.01 $hPa\ m^{-1} s$, lower panel) at 12UTC 19 February 1998. Negative values are dashed, and zero lines are omitted.

4 SUMMARY AND CONCLUSIONS

The GMS-5 and GOES-9 satellite wind data have been successfully incorporated into the MM5 model forecast via a 4D-Var approach. Three-day forecasts from the optimal initial conditions were carried out using both 90-km resolution and 30-km nested resolution MM5 models to explore the impact of these retrieved satellite wind data.

It is demonstrated that incorporation of the GMS-5 and GOES-9 satellite wind data added additional positive impact to the cyclone forecasts, in both cyclone intensity and track.

Assimilation of the satellite wind data increased the cyclonic zonal wind shear associated with the cyclone. The cold front intensity is also increased. The increased cyclonic shear is observed at the lower troposphere from 500 hPa to the surface during the cyclone intensifying period. The cyclone studied in this paper is a LC2 cyclone, which evolved from the cyclonic barotropic shear. The increase of the cyclonic shear after incorporation of the satellite wind data is of significant importance for the cyclogenesis.

The cyclone studied in this paper is located upstream of the GOES-9 wind data during the studied period from 12 UTC 19 through 12 UTC 22 February 1998. Comparison of the experiments with and without incorporating GOES-9 wind data indicated that downstream wind from GOES-9 satellite has marginal influence upon the mid-Pacific-Ocean cyclone.

The cyclone intensity is improved more significantly by increasing the model resolution and improving the model physics schemes than by modifying the initial conditions using satellite wind data. Assimilation of the satellite wind data has added value for the prediction of cyclone development. The best simulation results are from the experiment that used a simpler model with only one domain in the assimilation to reduce the computational cost and used a high resolution nested domain model with more advanced model physics for the model forecast.

Sensitivity analysis indicates that the prediction of this mid-Pacific-ocean cyclone is sensitive to the wind fields over the East Asia coast and Northwest Pacific region. Assimilation of GMS-5 satellite winds in that region incorporates stronger westerly winds from GMS-5 derived data, and results in improvement of the predicted cyclone intensity. However, sensitivity analysis also indicated that the cyclone intensity is more sensitive to winds at lower levels than at higher levels. Because no VIS winds are included in the assimilation due to darkness and most of the satellite-derived wind data are located in the middle to upper troposphere, further improvement of the cyclone forecast is anticipated if more observations of satellite-derived winds at lower levels are assimilated.

Acknowledgment

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